SMA Interferometry School 2020
Calibration II
Mark Gurwell, CfA
mgurwell@cfa.harvard.edu
Outline

• Further gain calibration considerations
  o what makes a good calibrator
  o use of multiple phase reference calibrators

• Phase self-calibration
  o why it can improve data, and at what cost
  o when is self-cal not appropriate?

• Flux calibration
  o use of solar system objects
  o desperate alternatives
Gain calibration
Gain calibration – Properties of a good calibrator

• Bright, point-like, with well known position

• ’Close’ to your target

• Low variability during observations
How ‘bright’ is bright?

Need SNR to determine phase (and amplitude) of calibrator to ‘required’ precision in a ‘reasonable’ time.

For $\text{SNR}_{\text{Thermal}} >> 1$, $\sigma_A \sim \sigma_\phi \sim 1/\text{SNR}$
Workin’ the numbers

\[
S_{\text{rms}} = \frac{2kT_S}{A\eta_A \sqrt{n_a(n_a - 1)\Delta\nu_{\text{IF}}\tau_0}} = 41 \text{ mJy}
\]

\(T_S = 300 \text{ K}\)
\(A = 28.27 \text{ m}^2 \text{ (6-m dish)}\)
\(\eta_A = 0.75 \text{ (aperture efficiency)}\)
\(n_a = 2 \text{ (1 Baseline)}\)
\(\Delta\nu_{\text{IF}} = 8 \text{ GHz}\)
\(\tau_0 = 60 \text{ s}\)
Workin’ the numbers

\[ S_{\text{rms}} = \frac{2kT_S}{A\eta_A \sqrt{n_a(n_a - 1) \Delta \nu_{\text{IF}} \tau_0}} \cdot = 41 \text{ mJy} \]

So, in this example, to reach an SNR of 10 (or 20) in 60 s, need to have a calibrator \( \gtrapprox 400 \) (or 800) mJy.
What is ‘close enough’?

Practical considerations –
- Rise/set of calibrator relative to target
  for 15°, up to 1 hour difference in rise/set times
- Atmospheric path differences
  for 15°, at low el, difference over one in airmass

In mm/submm may not have much choice, as ‘strong’ sources are not well distributed

Anecdotally, within 15 is ‘ok’, 10 degrees is ‘pretty good’ if you can get it, and within 5 degrees is ‘fantastic’.
Multi-calibrator Strategy

Useful to ameliorate calibrator distance issues

• Pick two (or more) similar strength calibrators, bracketing target such that one is always available

• Pick a weaker, closer calibrator and a stronger more distant calibrator.
Self-calibration
What is self-calibration?

Using the target data to determine gain solutions (typically phase, can include amplitude) via comparison with a ‘model’.

General phase calibration is a simple case of self-calibration, with the ‘model’ a point source at a known position (with the solutions interpolated to the target).
Why use self-calibration?

Improve the image signal-to-noise ratio and fidelity

Overcome dynamic range limitations

The atmosphere is similar, not identical, above the target and above the phase-ref

The phase-ref may be fainter than the target, so solutions are less accurate in both time and location
ALMA example (Anita M.S. Richards, UK ARC Node)

L2 Pup before & after self-cal

phase-ref sols only S/N ~400

~20-mas beam, ϕ-ref 3°
No self-cal: S/N ~400

self-cal p scan (90s) S/N ~2000

self-cal p 30s S/N 2640

ϕ, p self-cal S/N 2850
rms 35 μJy
theoretical 22 μJy
SMA example
(Titan, June 18, 2019 VEX at 267 GHz)

Dynamic Range~20

Dynamic Range~230
Caveats

Self-calibration disengages absolute astrometry; can’t use self-cal to determine a position ‘better’

Typically requires target strength to be strong enough for a good detection (antenna-based) in a time short enough to remove atmospheric fluctuations. If you have to average in time over too long, you will only decorrelate your source signal.

Model must be very accurate and/or number of baselines should be large. 8 antennas is a bit ‘light’, but if model is very good it works.
Flux calibration
Absolute Flux Calibration

“That’s no moon. It’s a space-station flux calibrator.”

(Reference: Butler 2012, ALMA Memo 594)
Visibility of a uniform disk

\[ \beta = R \sqrt{u^2 + v^2} \]

\[ \frac{J_1(2\pi \beta)}{\pi \beta} \]
Maximum ‘usable’ baseline lengths at 1mm

<table>
<thead>
<tr>
<th>Source</th>
<th>Diameter</th>
<th>Baseline (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jupiter</td>
<td>40&quot;</td>
<td>4</td>
</tr>
<tr>
<td>Mars (oppo)</td>
<td>25&quot;</td>
<td>7</td>
</tr>
<tr>
<td>Uranus</td>
<td>3.5&quot;</td>
<td>50</td>
</tr>
<tr>
<td>Neptune</td>
<td>2.3&quot;</td>
<td>70</td>
</tr>
<tr>
<td>Callisto</td>
<td>1.6&quot;</td>
<td>100</td>
</tr>
<tr>
<td>Titan</td>
<td>0.8&quot;</td>
<td>200</td>
</tr>
</tbody>
</table>

“That’s no moon. It’s a space station flux calibrator.”
Spectral features

$T_B$ (K)

Frequency (GHz)
Spectral features

![Graph showing spectral features with frequency on the x-axis and $T_B$ (K) on the y-axis. Peaks are labeled Titan.](image)
When No Flux Calibrator Data is Available

Sometimes, flux calibrator data is unusable or not obtained. What are your options?

- Rely on $T_{\text{sys}}$ calibration – under good atmospheric phase stability, will underestimate flux due to uncalibrated efficiency losses, but will be within about 15-30%, depending on frequency.

- Check if gain or passband calibrator sources have recently measured flux densities (may require interpolation):
  - SMA Database
  - ALMA Calibrator Database
Question time!